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- USSR -

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The actual course of combustion processes in technical apparatus is so complicated by secondary considerations that to take them into account would make analysis of the phenomena much more difficult. However, in any process of fuel combustion there occurs a number of common basic phenomena associated with the nature of the combustion process; this enables us to formulate a theory of the process regardless of the type of apparatus used. Among those phenomena which are of great interest is the transition from slow combustion to detonation, when the flame passes through the explosive mixture at a velocity of several kilometers per second.

Since the shock waves forming before the flame front play a substantial part in the formation of the detonation wave, an explanation of the role of shock waves in the organization of the combustion process is of special interest. The mechanism of formation of the shock discontinuity before the flame front can be reduced to the following: the expansion of gas during combustion near the closed end of a pipe leads to the formation of elementary disturbances, which propagate in the gas before the flame front. Since each succeeding disturbance propagates in the gas to which the preceding disturbances have imparted a certain velocity and have somewhat increased its temperature, the velocity of propagation of succeeding disturbances increases continuously. The shock wave forms where the elementary disturbances converge.

In the first approximation, the problem of the motion of a gas before a flame front during combustion of an explosive mixture in a pipe sealed on both ends can be reduced to the problem of the motion of a gas in front of a piston accelerating in accordance with the same law by which a flame actually accelerates. The problem of the motion of a gas enclosed in an infinite cylinder bounded on one end by an accelerating piston was solved by Hugoniot (1).

The problem, solved by Hugoniot analytically, is easily solved by the graphical method of characteristic curves (2). The shock wave forming before the flame front has a substantial effect on the further progress of the combustion process.

It is generally accepted that the existence before the flame front of a pronounced shock discontinuity, capable of igniting the mixture, is an essential condition for transition from slow combustion to detonation (3). Transition from slow combustion to detonation can be accomplished also in the case when a weak shock wave is formed before the flame front. The present work is in fact devoted to explaining the role of weak shock waves in the organization of the combustion process.

Experimental Procedure

For visualizing the process of the formation of a shock wave traveling before the flame front and unaccompanied by self-luminescence, an IAB-451 mirror-meniscus device was used.

Photography by the scanning method was supplemented by high-speed photography, which made it possible not only to judge the velocities of the flame and the shock waves, but also to record the fronts of the shock wave and flame during their interaction. An SVDSh-1000 superhigh-pressure mercury-arc lamp served as the light source in photography by the scanning method. For the light source during high-speed photography, a specially constructed pulse tube was used, generating high-repetition flashes. The design of this tube is described in detail in Reference (4).

The process was recorded on film placed on the inner surface of a uniformly revolving drum.

Since the sensitivity of the IAB-451 apparatus for a given light source depends on the width of the light beam passing the knife, the aperture of the collimator was increased to 0.7 mm for obtaining a clear picture of the development of the combustion process, free of any superfluous details.

Photography employed the so-called double-knife method; this made it possible to a considerable extent to diagram the diverging beams of luminescence from the explosion.

The investigation of the effect of shock waves on the development of the combustion process was conducted in stainless-steel pipes with a circular cross-section 42 mm in diameter and in pipes with a square cross-section of 36.5 X 36.5 mm.

One of the chamber sections was fitted with glass through which the process was recorded. The length of the viewable portion of the pipe was 200 mm. The length of the sections without glass was 200, 400 and 1000 mm. The overall length of the pipe could be varied from 400 to 2000 mm. By changing the position of the sections (sic) fitted with the glass it was possible to photograph the process in any part of the pipe. On one of the lids sealing the pipe was mounted a sparkplug for igniting the mixture; the other contained a valve for drawing off the air and feeding in the explosive mixture. Hydrogen-oxygen, methane-oxygen, and oxyacetylene mixtures were used as fuels.

Such a selection of mixtures makes it possible to study the formation of shock waves and their interaction with the flame front without the need of an extremely long combustion chamber, since combustion proceeds so rapidly in these mixtures that the shock wave forms at a relatively short distance from the point of ignition.

The hydrogen-oxygen and methane-oxygen mixtures were constituted by volume and stored in tanks without having been dried prior to being fed into the pipe. For preparing and storing the oxyacetylene mixtures, a special mixing unit was used, equipped with an agitator. The mixture was constituted according to pressure.

Experimental Results and Their Discussion

a) Formation of the shock wave before the flame front

All experiments to determine the distance between the points of ignition and formation of the shock wave X were conducted in a pipe with circular cross-section and 42 mm in diameter. The length of the pipe was selected so as to preclude the participation of disturbances, reflected from the end of the pipe, in the formation of the shock wave. The results obtained, describing the magnitude of X as a function of the percentage content of fuel in the mixture, are shown in Figure 1. The distance between the points of ignition and formation of the shock wave is laid out along the ordinate axis, and the percentage content of fuel in the mixture — along the abscissa (conversion to true content of fuel in the mixture was not performed). The points denote average values, obtained from 5-6 experiments.

Experiments with the hydrogen-oxygen mixtures were conducted with three initial pressures of the mixture: 400, 600 and 720 mm Hg. The methane-oxygen mixtures were ignited under an initial pressure in the chamber of 700 mm Hg, and the oxyacetylene mixtures — under a pressure of 400 mm Hg.

As seen from Figure 1, the curves for all three mixtures, describing the magnitude of X as a function of the percentage content of fuel in the mixture, have the form of curves with a minimum.

Figure 2 plots the value of X as a function of the initial pressure of the mixture in the pipe, for stoichiometric mixtures of hydrogen and oxygen, methane and oxygen, and acetylene and oxygen. With a rise in initial pressure the distance between the points of ignition and the appearance of the shock wave decreases. In the hydrogen-oxygen and oxyacetylene mixtures this is especially pronounced.

As already noted above, the distance between the points of ignition and appearance of the shock wave can, in the first approximation, be regarded as the distance at which a shock wave will form in front of a piston accelerating in accordance with the same law by which a flame actually accelerates.

According to Hugoniot, $X \sim \frac{a^2}{\frac{dv}{dt}}$, i.e., the distance at which the elementary compression waves overtake each other, to form a shock wave, depends on the velocity of sound in the medium and the acceleration of the piston.

Since the accelerating propagation of the flame is the cause of the elementary disturbances from which the shock wave is formed, the reason for the acceleration of the flame front in this stage of propagation takes on special interest.

Assuming that acceleration of the flame in the initial stage of propagation is caused by turbulence of the mixture before the flame front, Shchelkin (3) derived an expression relating the distance between the points of ignition and formation of the shock wave to the physico-chemical parameters of the mixture, in the form

$$X \sim \frac{a^2 d}{U_n^2}. \qquad (1)$$

The distance from the point of ignition to where the shock wave forms is proportional to the diameter of the pipe d; it increases with an increase in the velocity of sound and decreases with an increase in the normal velocity of the flame U_n.

With a change in the composition of the mixture, the value of X can vary as a result of a change in normal velocity as well as in the velocity of sound.

Let us consider the formation of a shock wave in oxyacetylene mixtures in which the velocity of sound is practically independent of the percentage content of the acetylene in the mixture. As the curve describing the dependence of the normal velocity of the flame of oxyacetylene mixtures on the percentage content of acetylene has two maxima (5), in contrast to similar curves for other fuels, the relationship between the value of X and the percentage content of acetylene in the mixture must be characterized by a curve with two minima.

In Shchelkin's formula, pressure is not represented clearly. In the range of pressure change studied by us, the normal velocity of the flame of oxyacetylene mixtures does not depend on pressure (6). Since the velocity of sound in the mixture also does not depend on the pressure, we can expect that the value of X is independent of the initial pressure of the mixture.

The experimental data obtained by us are in contradiction with formula (1).

An analysis of the course of the combustion process during the initial period of flame propagation shows that, after ignition of the mixture at the closed end of the pipe, there occurs in the reaction zone, together with a large drop in pressure, a significant increase in the specific volume of combustion products in comparison with the specific volume of the mixture before combustion. Combustion near the closed end of the chamber proceeds with ever-increasing pressure and temperature. Under these conditions it is doubtful whether it is expedient to link the acceleration of the flame in the initial stage of propagation with the normal velocity of the flame.

Role of Weak Shock Waves in the Organization of the Process of Combustion of Explosive Mixtures in Pipes

The shock waves forming before the flame front have a substantial effect on the course of the combustion process. Depending on in what stage of development the shock wave interacts with the flame front, combustion of the mixture in a pipe can be vibrational, it can

be characterized by flarebacks of the flame, or transition from slow combustion to detonation can occur.

To illustrate the above let us introduce several photographs of the combustion process.

In all the photographs the flame propagates horizontally while the film travels in the vertical direction. Scale markers, appearing at equal intervals from the ends of the viewable portion of the chamber, are registered in the form of black stripes running parallel to the time axis. Since the photographs were taken by the double-blade method, all optical nonuniformities -- both the regions of compression as well as the regions of rarefaction -- are recorded in the form of dark lines against a light background.

Figure 3 shows a time scan of the combustion of a stoichiometric hydrogen-oxygen mixture in a pipe with circular cross-section and a length of 40 cm.

The weak shock wave ($M = 1.5$) is reflected from the end of the pipe almost immediately after it is formed. The intensity of the diminishing shock wave is insufficient to ignite the mixture before the flame front. Approximately 200 microseconds after the shock wave is reflected from the end of the pipe, a new focus of combustion appears at this end, propagating at detonation velocity toward the first flame front. Propagation of the new focus of combustion does not always occur at detonation velocity.

Figure 4 (left) shows a time scan of the combustion of a stoichiometric methane-oxygen mixture near the butt surface of the pipe with square cross-section. On the right is a series of spark photographs of the same phase of the process. The flame front propagates from left to right. The compression waves, from which the shock wave is formed, can be seen clearly preceding the flame front. During reflection of the shock wave from the end of the chamber, there arises a new focus of combustion, propagating toward the flame front. However, in this case, combustion is not of a detonative character. The formation of the new focus of combustion is accompanied by a more intense glow than that of the first flame. This is natural inasmuch as at the end of the pipe a highly compressed mixture is burning.

The appearance of a new focus of combustion during reflection of the shock wave from the wall does not, of course, exhaust the various cases of the effect of weak shock waves on the progress of the combustion process.

Figure 5 shows a time scan of the combustion of a stoichiometric mixture of hydrogen and oxygen in a pipe with circular cross-section and 60 mm in length. It is readily seen that the distance from ignition to the point of formation of the shock wave does not depend on the length of the chamber if the chamber is sufficiently long to prevent the compression waves, reflected from the end of the chamber, from participating in the formation of the shock wave. Since the intensity of the developed shock wave decreases with the distance between the wave and the point of its formation, neither the direct nor the reflected shock wave is capable of igniting the mixture. Upon interaction of the flame front with the shock wave reflected from the end of the chamber, the flame front is repulsed. For a clear examination of the details of the interaction of the shock wave with the flame front, time scans of the combustion process were obtained, together with high-speed photographs of that phase of development of the process which interested us. Figure 6a (left) shows a time scan, while on the right is a series of high-speed photographs of the same phase of the process.

Clearly visible are the change in the form of the flame front during its interaction with the shock wave and the appearance of disturbances before the flame front, traveling counter to the shock wave.

Figure 6b shows the propagation of the flame after its interaction with the shock wave. As in the preceding photographs, on the left is a time scan of the process and, on the right, a series of high-speed photographs of the same phase of the process. The flame front, propagating through the medium previously "prepared" by disturbances arising during reflection of the shock wave from the flame front, assumes a unique form. Behind the flame front stretches the long comet's tail.

The interaction of a weak shock wave with the flame front can lead to the appearance of a detonation wave, as seen from Figure 7, which shows a time scan of the combustion of a stoichiometric mixture of methane and oxygen in a 1-meter chamber with circular cross-section. During combustion of the same mixture in a long chamber, when the shock wave reflected from the end of the pipe does not participate in the formation of the detonation wave, slow combustion develops into detonation at a distance of 120 cm from the sparkplug.

From the photograph it can be seen that the interaction of the weak shock wave with the flame front precedes the interaction of the shock wave with the waves which have formed later.

The propagation of the flame through a medium which has been "prepared" by the shock waves is of a detonative character.

The transition to detonation propagation of the flame can occur also without the flame front being acted upon by the shock wave forming before the flame front as a result of the accelerated propagation of the flame in the initial stage.

Such a development of the process is recorded in Figure 8, which shows a time scan of the combustion of a stoichiometric hydrogen-oxygen mixture in a 2-meter chamber.

The shock waves forming before the flame front in the predetonation stage play a substantial part in the transition from slow combustion to detonation. They create an accelerating flow of gas before the flame front, which facilitates the transition to detonation. The change in the form of the flame front during transition from slow combustion to detonation was examined in Reference (7).

Conclusions

1. Experiments revealed that the distance between the point of ignition and the point of formation of the shock wave is dependent on the composition and initial pressure of the burning mixture during combustion of explosive mixtures in a pipe closed at both ends.

2. The interaction of weak shock waves with the flame front was examined. It was shown that the detonation wave can arise both during interaction of the flame front with a weak shock wave formed in the initial stage of flame propagation, as well as from the propagation of the flame in a medium previously prepared by the shock waves forming in the predetonation stage of flame propagation. Transition from slow combustion to detonation can occur as a result of self-acceleration of the combustion process, caused by a weak shock wave reflected from the end of the pipe.

The work was conducted at the Laboratory of the Physics of Combustion, Power Engineering Institute, AS USSR, under the direction of A. S. Predvoditelev, Corresponding Member, AS USSR.

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